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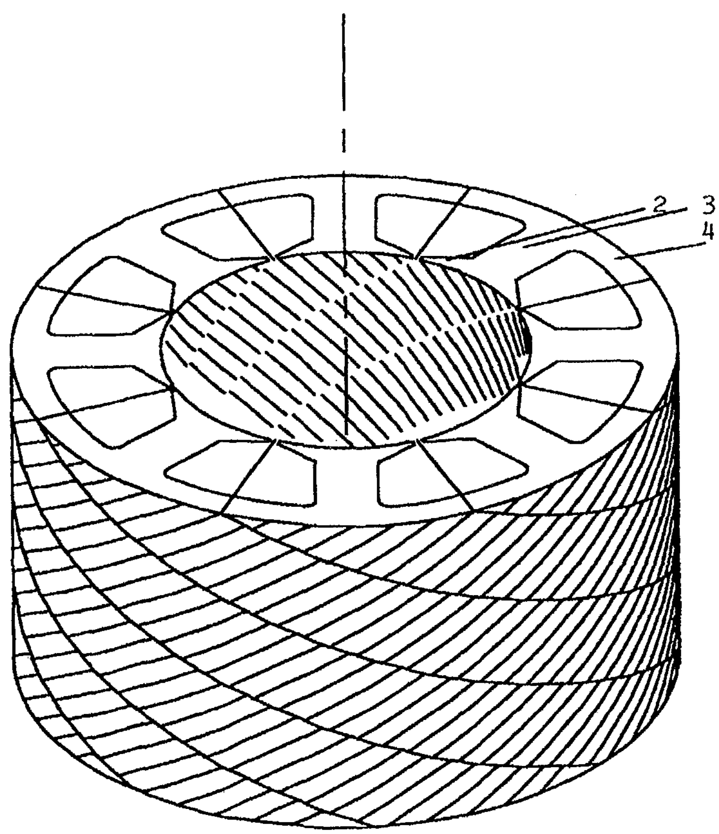
(57) Abstract

The electromechanical transducer consists of a stator (1) having a plurality of inner pole pieces (2) that describe a helix and a rotor having magnetic poles that similarly describe a helix. The rotor is constrained, for example by means of a spiral spring, so that the rotor can only move axially, no rotary movement is permitted. Each pole piece (2) of the stator is connected to a radial core (3) about which respective coils (5,6) are wound. Thus, the coils too describe a helix about the axis of the stator (1). The structure of the transducer results in the magnetic circuit having a helical component that contributes to the axial movement of the rotor. The transducer benefits from many of the advantages of rotary motors whilst providing linear movement.



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ELECTROMECHANICAL TRANSDUCER

The present invention relates to an electromechanical transducer of the electromagnetic type. In particular, but not exclusively, the present invention relates to linear motors and generators.

In conventional rotating electromagnetic motors the pole pieces, windings and magnets mainly run parallel to the motor axis thereby generating principal forces which are tangential and which in turn produce torques about the axis of the motor. In principal rotating motors have linear analogues where the rotor becomes a 'linear' rotor. In linear electromagnetic motors conventionally the various elements of the motors are aligned substantially orthogonal to the axis of the motor thereby generating forces which are parallel to the axis of the motor. The main difference between a rotary transducer and a linear transducer is that theoretically a rotary machine can undergo infinite angular motion without its geometry being altered, whereas in a linear machine where the stator and rotor are the same length, as one emerges from the other the geometry is altered. This means in practice that either the stator or the rotor must be extended to ensure that the one is always located wholly within the other.

An example of a conventional linear electromagnetic machine is described in US 4454426 in which a reciprocating element has permanent magnetic segments of alternating polarity separated by transitional regions. As the magnetic segments and transitional regions move linearly (axially) with respect to the stator, the magnetic segments cyclically reciprocate with the stator of the electromagnetic machine so as to produce periodic flux reversal through the coil provided on the stator. This type of design has a number of disadvantages. The motor design requires radial laminations, which are difficult to construct and result in unwanted voidage. Also, the rapid changes in the direction of magnetisation lead to cogging effects (i.e.

the rotor tends to stick in certain positions). Moreover, the end effects result in either of the end coils not experiencing full flux reversal (stator longer than rotor) or the end magnets not being fully utilised (rotor longer than stator).

More recent developments in linear motors are described in US 4620174 in which the replacement of alternate magnets with air gaps may reduce cogging and end effects. However, the disadvantage of radial laminations remains and the air gaps prevent the magnets from being fully utilised.

The present invention seeks to provide an improved electromechanical transducer which benefits from many of the advantages associated with the design and construction of rotating electromechanical devices whilst providing or utilising linear movement. The present invention also affords the unique feature that a value for the axial force generated can be derived directly from a measurement of torque. The value derived is independent of stator currents and rotor position, and is unaffected by the axial dynamics. The relationship between the axial force and the torque is a function only of the helical geometry. The torque can be sensed anywhere where the torque is transmitted. This feature is potentially advantageous in applications where the transducer is part of a control system or where a specified axial force is the required output of the transducer.

The present invention provides an electromechanical transducer comprising a stator having a plurality of coils and a magnetic assembly having a plurality of magnetic poles there being flux linkage between the coils and the magnetic poles, wherein the stator and the magnetic assembly are arranged for relative linear movement and at least one of the plurality of coils and the plurality of magnetic poles are arranged to describe a helical path about the axis of the transducer whereby the magnetic circuit includes a helical component.

In a preferred embodiment, the transducer also includes a plurality of magnetic circuit members located on the side of the magnetic assembly opposite to the side of the magnetic assembly facing the stator. The magnetic circuit members provide a low reluctance return path for magnetic flux passing through the magnetic assembly. Ideally, the magnetic circuit members comprise a relatively high permeability material such as laminations of soft iron. The magnetic circuit assembly may be cylindrical or solid.

The return path for the flux in the magnetic assembly may be contained within the magnetic assembly itself by using a particular type of magnetisation, for example, Halbach magnetisation. In this way the requirement for a separate circuit member can be greatly reduced or eliminated.

Ideally, the plurality of pole pieces of the stator and the plurality of poles of the magnetic assembly and the plurality of magnetic circuit members and coils are each arranged to describe helical paths about the axis of the transducer. In a preferred embodiment the helix angle for the magnetic assembly is different to the helix angle of the stator components.

Preferably, holding means are provided to constrain one or more of radial and rotational relative movement between the magnetic assembly and the stator and between the magnetic assembly and the magnetic circuit assembly. The holding means advantageously comprise appropriate combinations of conventional linear bearings such as plain, ball, roller or gas bearings.

In a preferred embodiment spiral spring members are connected to the magnetic assembly to enable linear relative movement of the magnetic assembly but to constrain radial and rotational relative movement.

In a further preferred embodiment two transducers of

opposite handedness may be coupled together thereby constraining rotational movement of each of the magnetic assemblies relative to the stator.

Each of the stator, magnetic assembly and the inner magnetic circuit members may be constructed from a relatively high permeability material with low electrical conductivity. Alternatively, they may be constructed from a plurality of laminations stacked together. The plane of the individual laminations may be orthogonal to the axis of the transducer. Ideally, though, so as to minimise eddy currents, the plane of the individual laminations is arranged to describe a helical path about the axis of the transducer.

In one embodiment of the transducer the magnetic assembly may be discontinuous about the axis of the transducer and may extend over a predetermined arc of the transducer. With this embodiment assembly of the transducer is simplified as the need for the inner elements of the transducer to be fed along the axis of the outer elements is obviated.

It will be understood that the present invention may be applied in substantially all circumstances where conventional electromechanical transducers may be employed. Moreover, the various embodiments and many of the adaptations of such electromechanical transducers also apply to the present invention. In particular but not exclusively, the present invention is suited for use as a synchronous machine, an induction machine, a reluctance machine, a DC machine with commutation, a stepper motor, two/multi pole machines, and with single/poly or switched phase winding variations. Also, with the present invention, although the rotor is often positioned within the stator this relationship may be reversed in appropriate circumstances. In the case of variable reluctance and inductance motors employing the present invention, these motors can be designed without permanent magnetic material. This in turn can reduce costs, and lead to more robust designs.

Embodiments of the present invention will now be described by way of example with reference to the accompanying drawings, in which:

Figures 1a - 1c are cross-sectional views of an electromagnetic motor in accordance with the present invention in three separate axial positions;

Figures 1d - 1f are plan views of the motor of Figures 1a - 1c showing the three axial positions of the motor;

Figure 2 is a perspective diagrammatic view of the rotor of the motor of Figures 1a - 1f;

Figure 3 is an enlarged view of the motor in cross-section of Figure 1a;

Figures 4a - 4f are diagrams of the relationship between the poles and pole pieces of a motor in accordance with the present invention;

Figures 5a and 5b are cross-sectional diagrams of the flux paths between the poles and the pole pieces for two axial positions showing a transducer in accordance with the present invention in the form of a generator;

Figures 6a and 6b are diagrams of the construction of a stator in accordance with the present invention;

Figures 7a and 7b are diagrams of an alternative motor in accordance with the present invention;

Figure 8 is a perspective diagram of a rotor for an induction motor in accordance with the present invention;

Figures 9a and 9b are diagrams showing a variable reluctance motor in accordance with the present invention;

Figure 10 shows a further development of the reluctance motor of Figures 9a and 9b;

Figures 11a and 11b show a further alternative embodiment of a linear motor in accordance with the present invention;

Figures 12a and 12b show a motor in accordance with the

present invention in a linear compressor assembly; and

Figure 13 is an enlarged diagram of the spiral spring of Figures 12a and 12b;

Figures 14a and 14b show the magnetisation of a rotor using Halbach magnetisation; and

Figure 15 shows a motor in accordance with the present invention using Halbach magnetisation in a linear compressor assembly.

For the purposes of the following description the electromechanical transducer will be described with reference to its function as a motor. It will of course be understood that the transducer may be employed in a wide variety other applications whilst still relying upon the same underlying principles.

The basic motor comprises a static outer coil and magnetic circuit assembly herein referred to as the outer stator 1; a moving magnet assembly herein referred to as the rotor 7; and an inner magnetic circuit assembly herein referred to as the inner cylinder 10. The motor has a helical geometry which enables the motor to benefit from the constructional advantages of a rotating motor structure whilst utilising or providing linear motion. Thus, the pole pieces, windings and magnets are twisted to provide a helical geometry about the motor axis. The various elements of the motor may follow a continuous helical path about the motor axis. Alternatively, the elements may comprise discrete portions of the helical path. This results in the forces generated having both tangential and axial components with the tangential component of the forces being absorbed so that only axial movement of the motor is permitted. The helix angles of the rotor and stator maybe different to reduce cogging forces.

The outer stator 1 is constructed from a plurality of laminations of soft magnetic material which are stacked together. The shape and angular orientation of the laminations is such as to form a plurality of rotationally symmetric magnetic circuits with inner helical pole pieces 2. Each

lamination consists of the plurality of inner pole piece elements 2 each connected to a respective radial core 3 which are in turn connected to a single common outer ring 4. With all the laminations stacked together, coils 5, 6 are wound around corresponding radial cores 3. The stator coils are connected together such that their induced emfs add. They can be connected in various series/parallel arrangements to match differing voltage/current inputs. For neighbouring coils 5, 6 to work together the coils are connected with an opposite sense as the magnetic fluxes through them at any instant will be in opposite directions.

The rotor 7 comprises a plurality of helical segments 8, 9 joined together to form a cylinder. The number of pole pieces in the stator 1 may be selected to be equal to the number of rotor poles or it may be higher e.g. for multiphase operation. Alternate segments 8 are radially permanently magnetised magnets, all magnetised in the same direction for example north poles on the outer surface. The intervening segments 9 are laminated soft iron pole pieces. These pole pieces 9 become magnetised in a direction opposite to the magnet segments 8 so that the outer surfaces of neighbouring segments have alternate poles. The rotor 7 is secured to the outer stator 1 in any suitable manner to ensure the rotor is only permitted linear (axial) movement relative to the stator 1. Both radial and rotation relative movement is substantially prevented. Additionally, the axial lengths of the stator 1 and the rotor 7 are selected so that at the extremities of the movement of the rotor 7, the rotor 7 remains wholly within the stator 1.

The inner magnetic assembly 10 comprises a plurality of laminations of soft iron stacked together to form a cylinder. Ideally, the axial length of the inner magnetic assembly 10 is selected so as to be substantially equal to the axial length of the stator 1. The inner magnetic assembly 10 is preferably connected by any suitable means to the stator 1. The inner magnetic assembly 10 functions to connect the alternating poles

of the rotor in a low reluctance path. The inner magnetic assembly 10 is not essential but enables stronger fluxes to be generated or used in the transducer. In addition, the inner magnetic assembly may be made as a solid inner core instead of a cylinder. Where the motor is intended for use as the drive for a compressor, the inner magnetic assembly may describe the walls of the piston member. Also, the inner magnetic assembly may be integrated with the rotor where the extra moving mass can be tolerated. This simplifies construction and removes two air gaps.

In order to constrain the radial and rotational movement of the rotor whilst enabling its axial movement, suitable combinations of conventional linear bearings may be employed such as ball bearings, roller bearings, plain bearings or gas bearings. For example, a non-standard linear bearing, having for example a square cross-section, may be employed. If two similar machines with opposite handedness are coupled on a common axis the torques will be in opposition thereby preventing rotation and ensuring only axial motion. Alternatively, spiral springs have the property of low axial stiffness whilst having high radial and torsional stiffness. When mounted in pairs spiral springs behave as bearings and are capable of affording accurately constrained motion. Spiral springs have the additional advantage that as they have no contacting surface they are not subject to the same wear. Moreover, the spiral springs may also be used to provide electrical connections between the stator and rotor where this is required.

Although not described in detail it is to be understood that the electrical connections in general and the connections to the coils are wholly conventional and no further description is considered necessary. As the coils 5, 6 on the stator inherently project beyond both ends of the stator 1 electrical connections can readily be made as for a conventional rotary machine. The same is also true of transducers where the rotor 7 contains energised coils. To ensure that the direction of movement of the rotor is reversed at the extreme ends of its motion, the individual coils may be

suitably driven to control the motion of the rotor. Alternatively, the rotor may be biased by means of a spring member, for example, to force the direction of movement of the rotor to reverse.

The relationship of the various components of the motor are shown in Figures 1a to 1f. In Figures 1a and 1d the rotor 7 is positioned at the extreme left of its travel (as seen in the Figure), in Figures 1b and 1e the rotor 7 is positioned approximately half way between the two extremes of its travel and in Figures 1c and 1f the rotor is positioned at the extreme right of its travel. The change in the positional relationship between the pole pieces 2 of the stator 1 and the segments 8, 9 of the rotor 7 may be clearly seen as the rotor 7 moves from its extreme left position to its extreme right position. The relationship between the pole pieces 2 and the segments 8, 9 is shown in the enlarged partial cross-section of Figure 3 for the rotor 7 in either its extreme left or right position. In Figure 2 the helical nature of the segments 8, 9 of the rotor 7 may be seen more clearly.

Turning now to Figures 4a to 4f, these Figures show the varying relationship between the cylindrical surfaces of the pole pieces 2 and the segments 8, 9 in planar form (i.e. unwrapped). In Figure 4a the rotor 7 is in approximately its mid position with each outer pole piece 2 having two segment halves 8, 9, one north and one south, adjacent it. With no current flowing through the coils 5, 6 no resultant force acts on the rotor 7. If a current is passed through the coils 5, 6 the outer pole pieces 2 become alternate north and south poles, as shown in Figure 4b. The rotor 7 therefore tries to align itself with the magnetisation of the pole pieces 2 and with no constraints, the helical geometry of the segments of the rotor 7 would enable alignment by both axial and rotational movement. However, as mentioned earlier rotational movement of the rotor is prevented, therefore the rotor 7 moves axially until the poles of the segments 8, 9 are appropriately aligned with the opposing magnetisation of the pole pieces 2 as shown in Figure 4c. If an alternating current is applied to the coils 5, 6

so that the magnetisation of the pole pieces 2 varies with time an alternating axial force/motion is achieved. Figures 4d to 4f show the motion of the rotor 7 in response to an opposite force.

In Figures 5a and 5b cross-sectional views of an electromechanical transducer are shown, similar to those of Figures 1a to 1c. However, the transducer of Figures 5a and 5b is described in terms of its function as a generator. In Figure 5a the rotor 7 is positioned approximately half way between its left and right extreme positions. In this position, as described earlier, each pole piece 2 is adjacent two half segments of poles 8, 9 of the rotor and so the flux coming out of one segment pole equals the flux going into the other segment pole whereby the net flux through all the cores equals zero and there is no flow through the outer ring 4 of the stator. If the rotor 7 is now moved axially so that the poles of the segments 8, 9 become more closely aligned with individual pole pieces 2, a net flux will begin to flow through the cores 3 and the outer ring 4 with the maximum flow occurring when the poles are fully aligned with the pole pieces 2. If the rotor 7 is now returned to its original position and is then moved in the opposite direction the flux in each pole piece is caused to flow in the opposite direction. Thus, a reciprocating linear, i.e. axial motion of the rotor 7 within the stator 1 results in a reversing flow of flux through the cores 3 which in turn induces an alternating emf in the coils 5, 6.

The above descriptions of the transducer as a motor and generator have been for single phase operation where the number of stator poles and rotor poles is equal. Of course, the number of stator poles can be made higher than the number of rotor poles. This leads to phase differences in flux variation in different stator coils and allows multi-phase operation as for rotary machines. Also, as for rotary machines, the transducer's mode of operation will generally be synchronous. Non-synchronous operation is possible in induction machines where rotor

magnetisation is induced.

The above is a somewhat simplified description as the helical geometry of the transducer generates magnetisation vectors which have axial components and flux paths with helical components, that is the flux paths are not planar. The effect of the helical component of the flux paths is addressed in the optimisation of the construction of the magnetic circuit components. Conventionally, the magnetic circuit components are constructed by stacking planar lamination layers with the plane of the layers being orthogonal to the axis of the transducer. A helical transducer may be constructed in this manner, however, the transducer will experience losses due to eddy currents as the flux will not lie wholly within the plane of the laminations. In order to minimise losses, the laminations also need to have a helical geometry as shown in Figures 6a and 6b. Single helical laminations such as those shown in Figure 6a combine to form helical segments which in turn combine to form the complete circuit as shown in Figure 6b. In this way the flux is confined within the planes of the laminations. Alternatively, the eddy current losses can be substantially avoided by using solid high permeability materials with low electrical conductivity.

Figures 7a and 7b correspond to Figures 5a and 5b, however, Figures 7a and 7b show an alternative arrangement of the transducer functioning as a generator with the rotor 7' positioned outside of the stator 1'. In Figure 7a the rotor 7' is in its half way position with two halves of two neighbouring segments 8', 9' being located adjacent each pole piece 2' and with no flux flowing through the cores 3'. In Figure 7b individual segments 8', 9' are aligned with respective pole pieces 2' resulting in flux flowing through the cores 3' and the outer ring 4' of the stator. Also the outer magnetic circuit may be integrated with the rotor with the same advantages as for the transducer in Figures 5a and 5b.

Turning now to Figure 8, a further alternative arrangement of the

rotor of the electromechanical transducer is shown for use in a linear induction motor. The rotor consists of laminations of soft permeable magnetic material 20, for example soft iron, with shorted loops 21 of an appropriate conductor, for example copper or aluminium. Thus, this arrangement of the rotor is the helical equivalent of a squirrel cage of an induction motor. The operation of the induction motor employing the helical rotor is the same as for a conventional induction motor, with the moving fields in the stator inducing currents in the loops of conductors 21. The resulting induced field interacts with the applied field to produce a resultant force.

In a further alternative, a single magnetisable component may be used that has isotropic magnetisation properties and which can be magnetised so as to give any desired field distribution. Halbach magnetisation is an example of this type of non-binary magnetisation and is described with reference to rotary machines in “Design and analysis of multi-pole Halbach (self-shielding) cylinder brushless permanent magnet machines”, K Atallah, D. Howe and P.H. Mellor pages 376 –380, IEE Proceedings of EMD 97, Cambridge UK 1997 the contents of which is incorporated herein by reference. Halbach magnetisation can be advantageously used to reduce the effect of cogging. This can be done by ensuring that an approximately sinusoidal variation in magnetisation that follows a generally helical path is permanently induced in the rotor. As shown in Figure 14a, using Halbach magnetisation a cylindrical rotor has a plurality of helical poles induced in its outer diameter. However, closer examination of the magnetisation of the rotor in a path normal to the helical path of the poles (line A-A) reveals the changes in the direction of magnetisation to be gradual, i.e. not limited to binary, two pole magnetisation directions. As the direction of magnetisation changes gradually, the need for a return path inside the rotor may be eliminated or greatly reduced. The cylinder can also be magnetised so that the poles

are on its inner diameter and the outer diameter is approximately self-shielded.

In Figures 9a and 9b a helical variable reluctance motor is shown with Figure 9b showing in perspective the three dimensional shape of the rotor 22. The stator 23 is similarly shaped to adopt a helical or twisted form so that the coils 24 extend helically along the axial length of the stator. The rotor 22 has four salient poles and the motor operates by energising the stator phases (i), (ii), (iii) in an appropriate sequence. A stepper motor development of the reluctance motor of Figures 9a and 9b is shown in Figure 10. The rotor 22 and stator 23 of the stepper motor have the same general form as the reluctance motor of Figures 9a and 9b. However, the pole pieces 25 and the poles 26 are castellated to provided finer control of the motion of the rotor 22. With this arrangement both the rotor and the stator may be made out of solid material instead of being constructed from laminations. Of course, the same is true of all of the transducers described herein, where appropriate. The solid material is preferably a relatively high permeability material with low electrical conductivity, for example sintered/bonded soft magnetic composite powders.

In Figures 11a and 11b a further alternative design of a helical linear motor is shown in which the helical poles do not form a closed cylinder. Instead the rotor 30 is split which enables the inner component 31 to be continuously supported. This in turn means that the overall size of the transducer and therefore the overall travel of the rotor can be greatly increased. Additionally, by splitting the rotor 30 in this manner the assembly of the transducer is simplified as this construction does not require the inner component to be fed through the outer component.

In Figures 12a and 12b a helical motor is shown as part of a linear compressor assembly. The stator 1 is mounted on a support assembly 40 which in turn is connected to a mounting plate or base plate 41. The inner magnetic assembly 10 is secured in a static relationship to

the stator 1 by means of a flange or inner plate 42. The inner plate 42 is shown in Figure 12b, which is a cross-section along the line A-A of Figure 12a, with three slots 43. Of course alternative numbers of slots may be employed as appropriate. The rotor 7 is positioned in the gap or channel between the stator 1 and the inner magnetic assembly 10 and is concentrically aligned therewith. The axial length of the rotor 7 is less than the length of both the stator and inner magnetic assembly so that at the extremes of travel of the rotor, the rotor remains within the channel defined by the stator 1 and the inner magnetic assembly.

Adjacent the base plate 41, the rotor 7 is mounted on a rotor support assembly 44 comprising three posts 45 which project through a respective slot 43 in the inner plate 42 for connection to an inner end of the rotor 7. The posts 45 are secured to the housing of the compressor assembly be means of biasing members 46, preferably in the form of spiral springs. The outer end of the rotor 7 is connected to a cylindrical wall 47 which projects beyond the ends of the stator 1 and the inner magnetic assembly 10. The cylindrical wall 47 is similarly secured to the compressor housing by means of biasing members or spiral springs 46. The cylindrical wall 47 is also connected to or integral with a piston head 48 which is located within a compressor chamber 49 situated within and coaxial with the inner magnetic assembly 10. With this arrangement, linear movement of the rotor 7 is transmitted via the cylindrical wall 47 to the piston head 48. The movement of the rotor 7 is thereby reciprocated by the piston head 48 within the compressor chamber 49. The compressor chamber 49 has an outlet 50 which is suitably valved (not shown) to ensure compression takes place within the chamber 49 by virtue of the movement of the piston 48. The spiral springs 46 are connected to the compressor housing by means of spacers and other suitable fasteners. An example of a spiral spring 46 employed with the linear compressor assembly is shown in Figure 13.

In Figure 15 an alternative twin piston/cylinder compressor

assembly is shown in which like reference numbers are employed as appropriate. The stator 1 is again mounted on a support assembly 40 which in turn is connected to a mounting plate 41. However, in this embodiment the rotor 7 is a single component that has been magnetised using Halbach magnetisation thereby enabling the omission of the inner magnet assembly. The rotor 7 directly links axially opposed piston heads 48 in their respective chambers 49. As before, the rotor 7 is secured to the housing of the compressor assembly by biasing means 46 such as a spiral spring. In addition, a torque transducer 51 is mounted adjacent the spiral spring to provide a measure of the axial force generated by the motor. This measurement is independent of stator currents and rotor position and is unaffected by the axial dynamics, as such the torque measurement is a function only of the helical geometry.

As mentioned earlier it will be apparent that the rotor may be positioned within the stator or vice versa depending upon the particular application concerned. Additionally, the helical soft iron segments 9 of the rotor may be substituted with magnets magnetised in the opposite radial direction to the magnet segments 8. This would enable a higher flux to be achieved or a greater clearance between the rotor and the stator. Alternatively, the segments 9 may be in the form of air gaps or be comprised of a non-magnetic filling material. In general the greater the air gap between the rotor and the stator the lower the maximum flux which may be achieved. On the other hand a greater air gap can permit a lighter weight rotor to be employed. Also, the inner magnet circuit assembly may be secured to the rotor so that it moves with the rotor. This alternative structure has the disadvantage of increasing the overall weight of the moving mass. Reference has been made herein to the segments 8 of the rotor being permanent magnets. For small machines the segments 8 may be permanent magnets but for larger machines it may be preferable to employ electromagnets.

It will be appreciated that the stator poles with concentrated windings, as shown in Figure 3, may be replaced with distributed windings in slots such as is standard practice in rotary machines. This tooth/slot design and the distributed windings allow the cogging forces to be reduced and the emf waveform to be controlled. In a further alternative the flux linkage between the magnetic poles and the coil may be achieved principally by non-ferromagnetic materials. This eliminates the effect of cogging but also reduces the flux linkage.

With the transducer described herein a helical geometry is employed to provide a transducer construction based on a rotary machine which utilises or provides linear movement. The transducer has the advantage that flux leakage can be minimised by enclosing the flux paths in helically arranged laminations. Also, the net torque of the helical machine can be eliminated by connecting two similar machines with opposite handed helices on a common axis. The transducer is suited for use in all circumstances where a linear motor might be employed. For example, in transport systems where continuous linear movement is desired; in positional control applications where intermittent linear movement is desired and with vibrators such as loud speakers; and in linear oscillation applications for example as a compressor/expander and as a generator.

CLAIMS

1. An electromechanical transducer comprising a stator having a plurality of coils and a magnetic assembly having a plurality of magnetic poles there being flux linkage between the coils and the magnetic poles, wherein the stator and the magnetic assembly are arranged for relative linear movement and at least one of the plurality of coils and the plurality of magnetic poles are arranged to describe a helical path about the axis of the transducer whereby the magnetic circuit includes a helical component.

2. The electromechanical transducer as claimed in claim 1, wherein the stator includes a plurality of core elements on which the plurality of coils are mounted and associated pole pieces.

3. The electromechanical transducer of claims 1 or 2, wherein a magnetic circuit member is provided on the side of the magnetic assembly opposite to the side of the magnetic assembly facing the stator.

4. The electromechanical transducer of claim 3, wherein the magnetic circuit member is integral with the rotor and moves as part of the rotor.

5. The electromechanical transducer of any one of claims 1 to 4, wherein at least the plurality of coils of the stator and the plurality of magnetic poles of the magnetic assembly are all arranged to describe helical paths about the axis of the transducer.

6. The electromechanical transducer as claimed in claim 5, wherein

the angle of the helical path of the plurality of coils is different to the angle of the helical path of the plurality of magnetic poles of the magnetic assembly.

7. The electromechanical transducer as claimed in any one of the preceding claims, wherein holding means are additionally provided to constrain at least rotational relative movement between the magnetic assembly and the stator.

8. The electromechanical transducer of claim 7, wherein the holding means is in the form of one or more spiral springs.

9. The electromechanical transducer of any one of claims 1 to 6, wherein two transducers of opposite handedness are coupled thereby constraining rotational movement of the magnetic assemblies relative to the stator.

10. The electromechanical transducer as claimed in any one of claims 2 to 9, wherein at least one of the plurality of core elements and the associated pole pieces of the stator, the magnetic circuit member, and intervening segments interposed between the magnetic poles of the rotor consists of high permeability material.

11. The electromechanical transducer as claimed in any one of the preceding claims, wherein at least one of the stator, the magnetic assembly and the magnetic circuit member consists of a plurality of laminations stacked together.

12. The electromechanical transducer of claim 11, wherein the planes of the individual laminations describe a helical path about the axis of

the transducer.

13. The electromechanical transducer of any one of the preceding claims, wherein the magnetic assembly consists of a single component having isotropic magnetisation characteristics whereby the magnetic assembly has a non-binary magnetic field distribution.

14. The electromechanical transducer of any one of the preceding claims, further including a torque transducer for measuring the axial force generated by the electromechanical transducer.

15. The electromechanical transducer of any one of the preceding claims, wherein the rotor does not form a closed cylinder.

16. A compressor having an electromechanical transducer as claimed in any one of the preceding claims connected to a piston and cylinder arrangement.

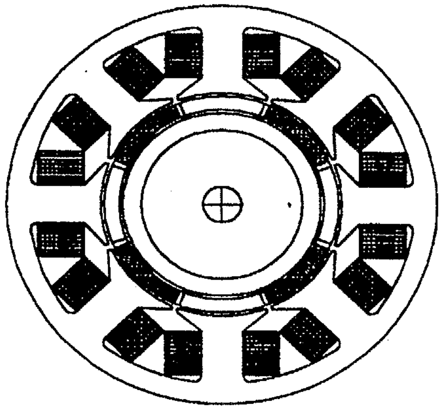


FIGURE 1c

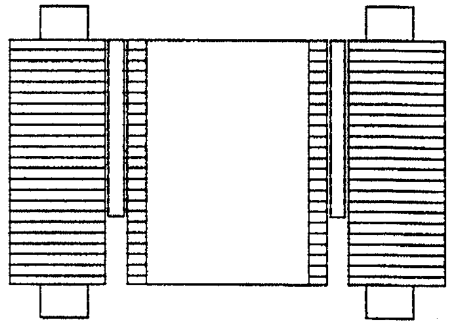


FIGURE 1f

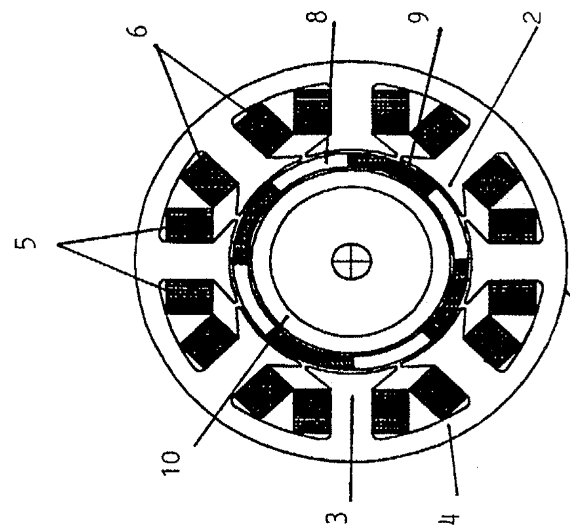


FIGURE 1b

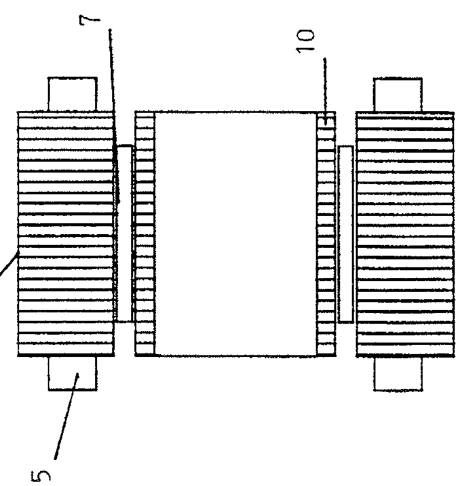


FIGURE 1e

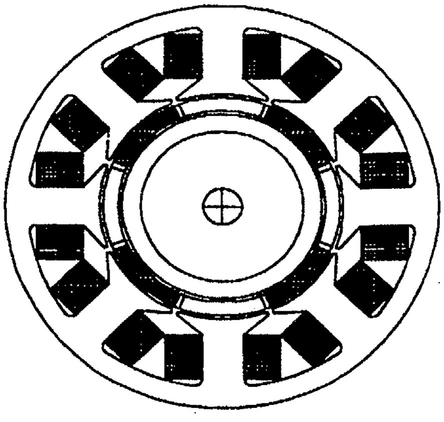


FIGURE 1a

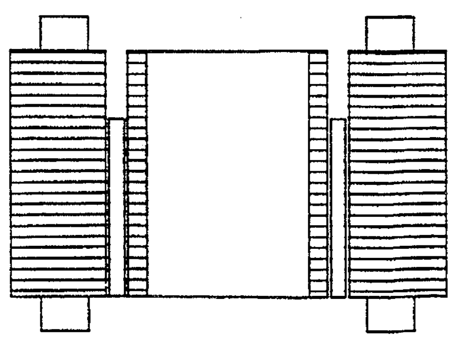


FIGURE 1d

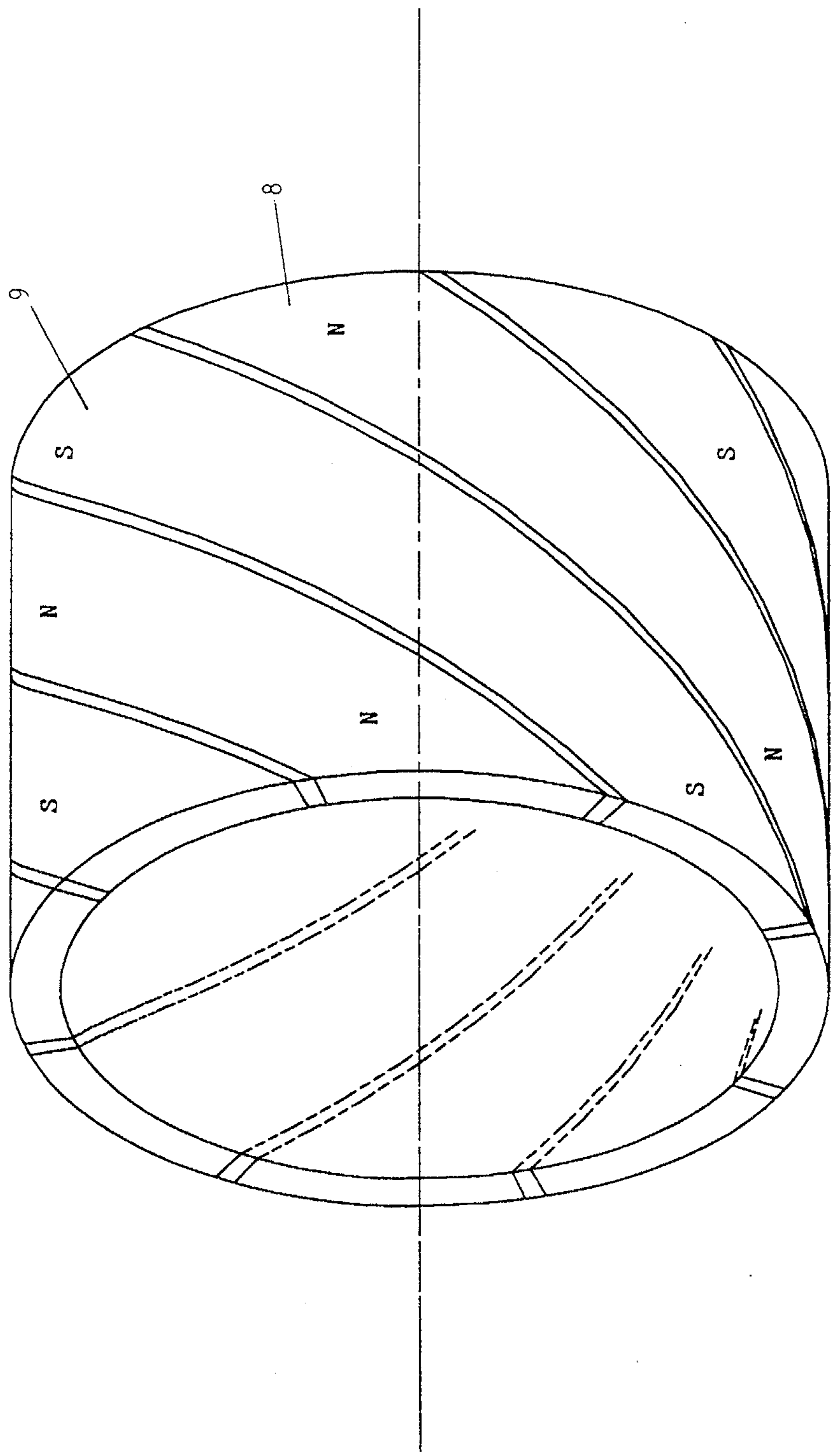


FIGURE 2

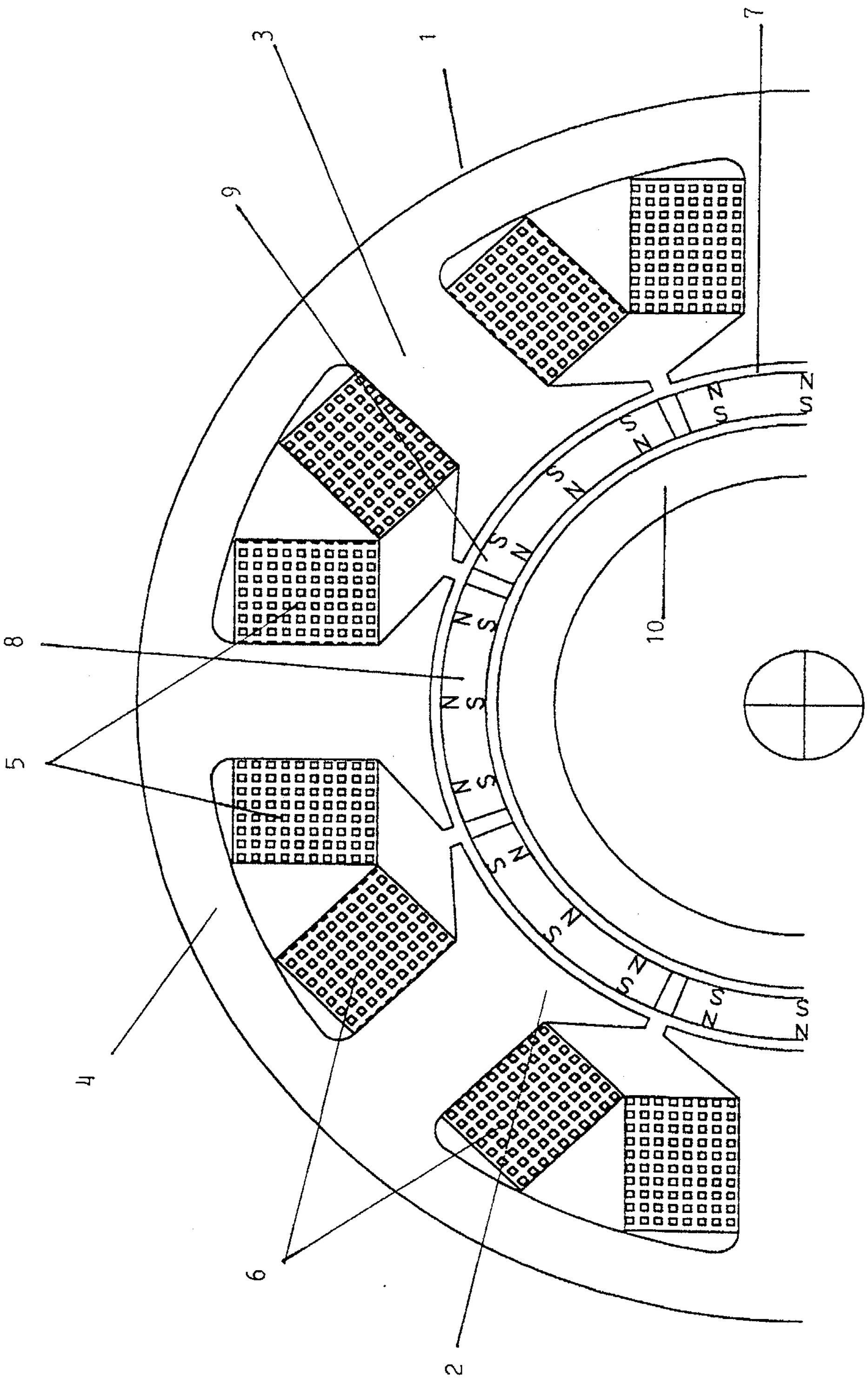


FIGURE 3

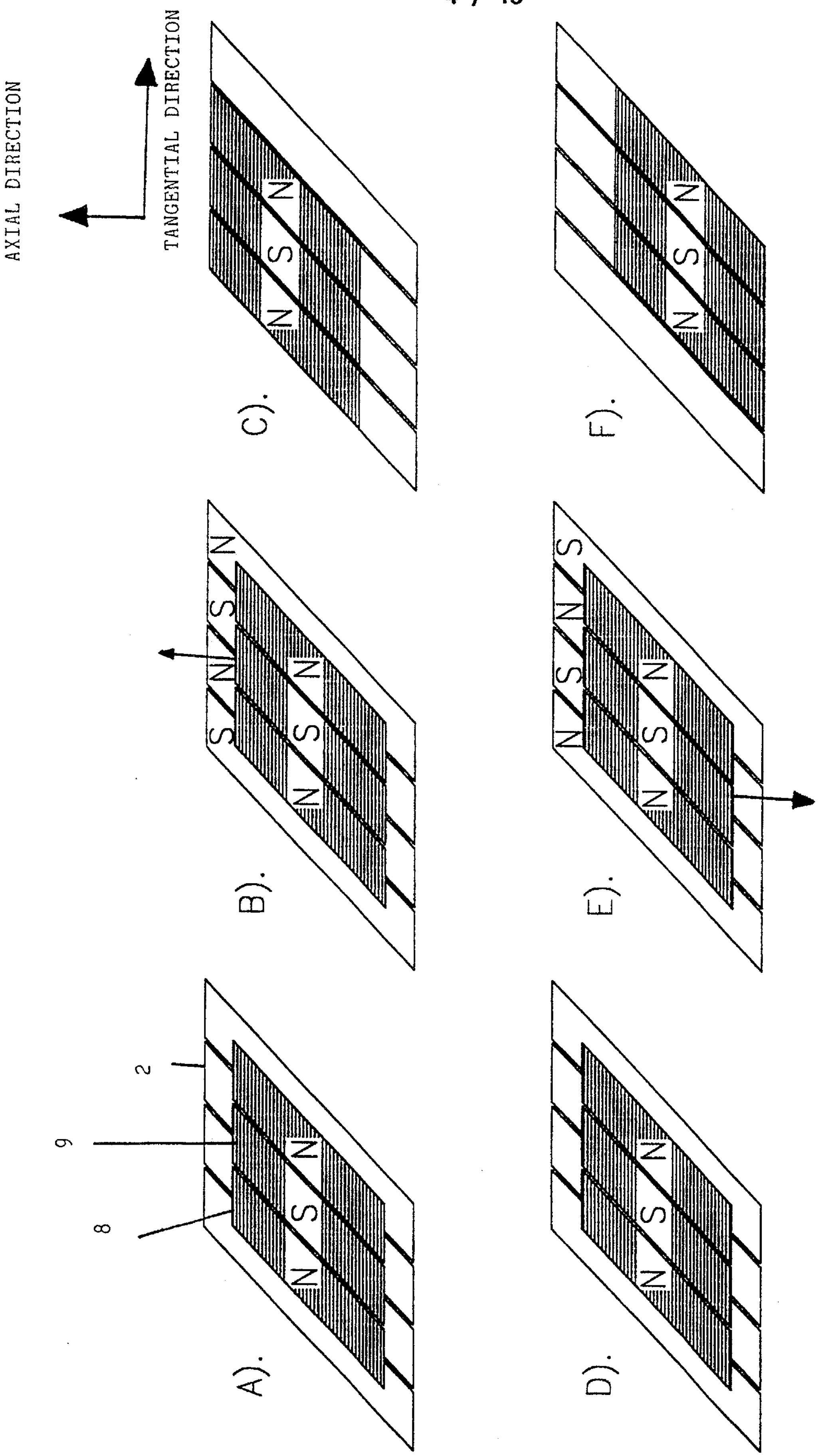


FIGURE 4

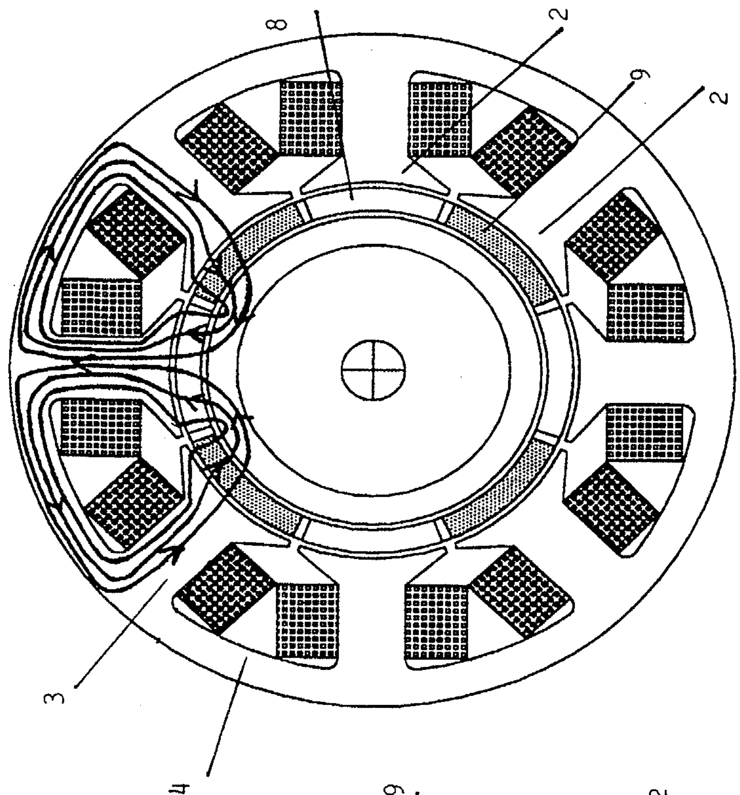


FIGURE 5b

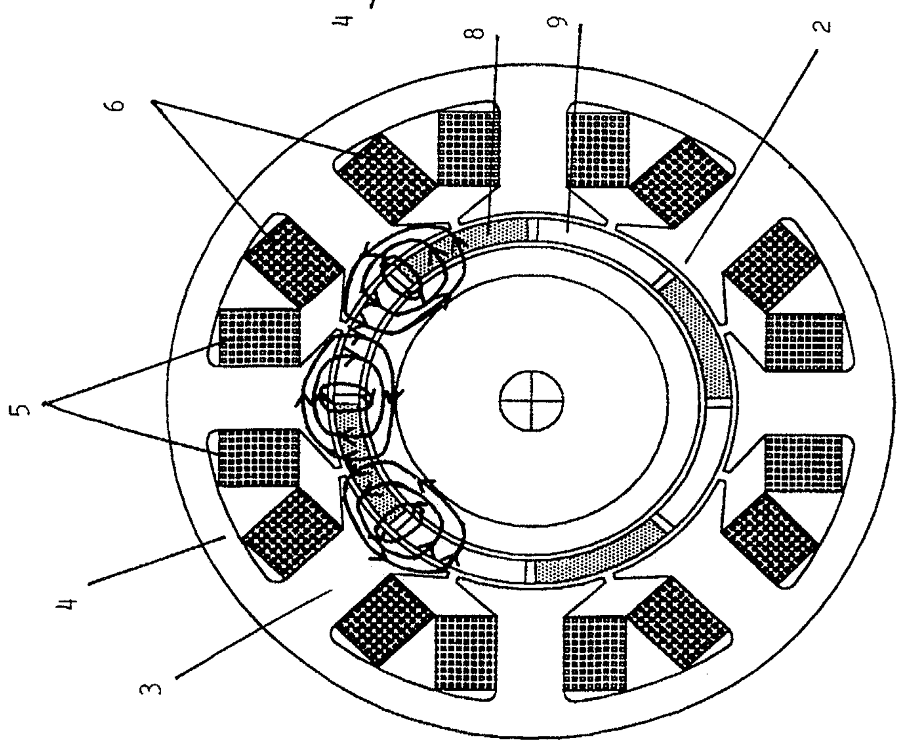


FIGURE 5a

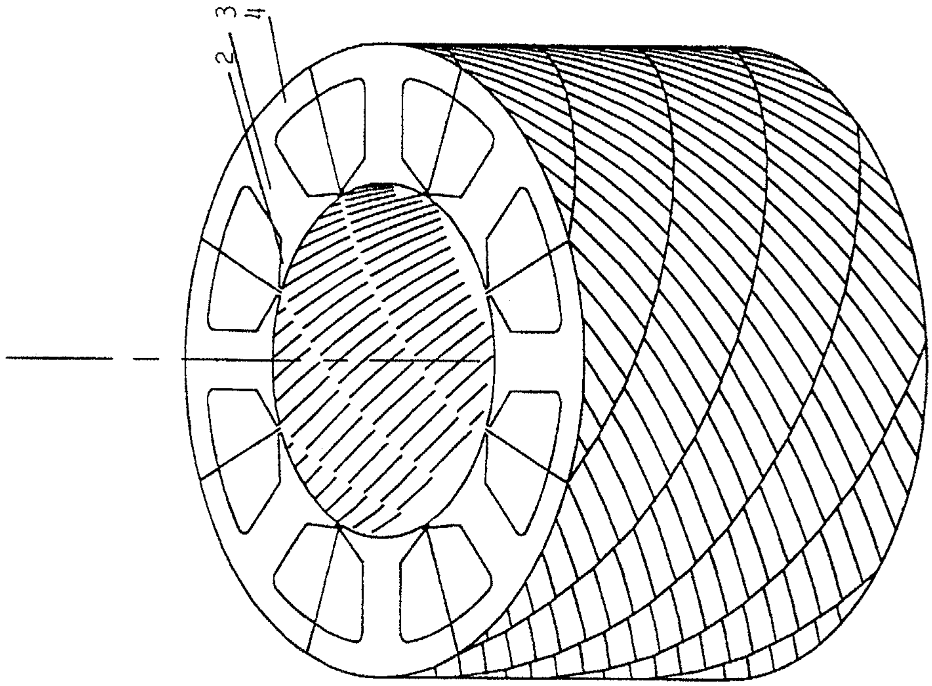


FIGURE 6b

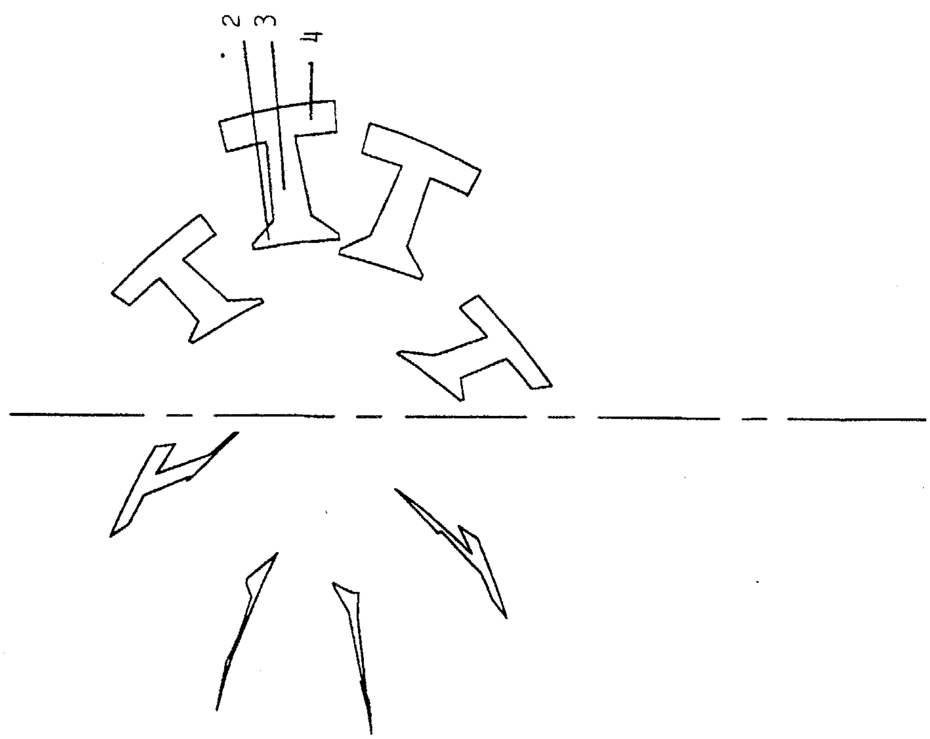


FIGURE 6a

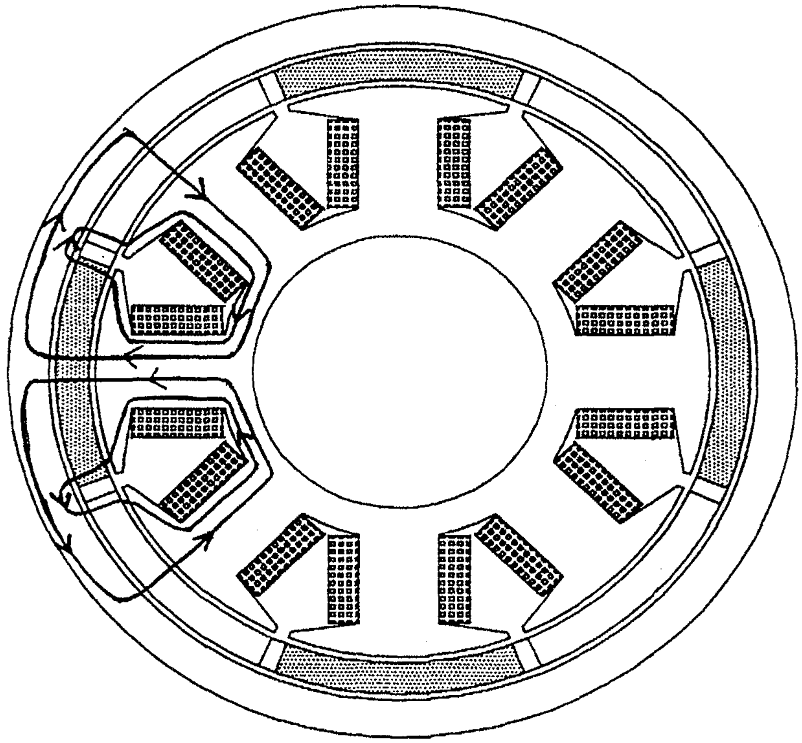


FIGURE 7b

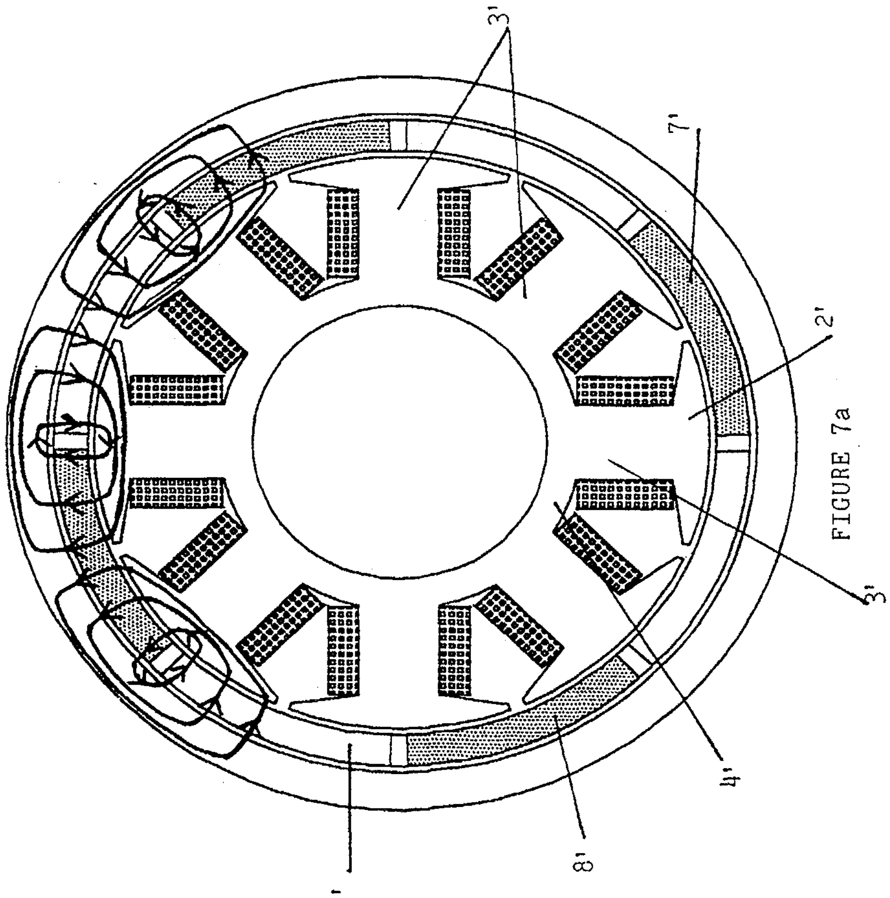
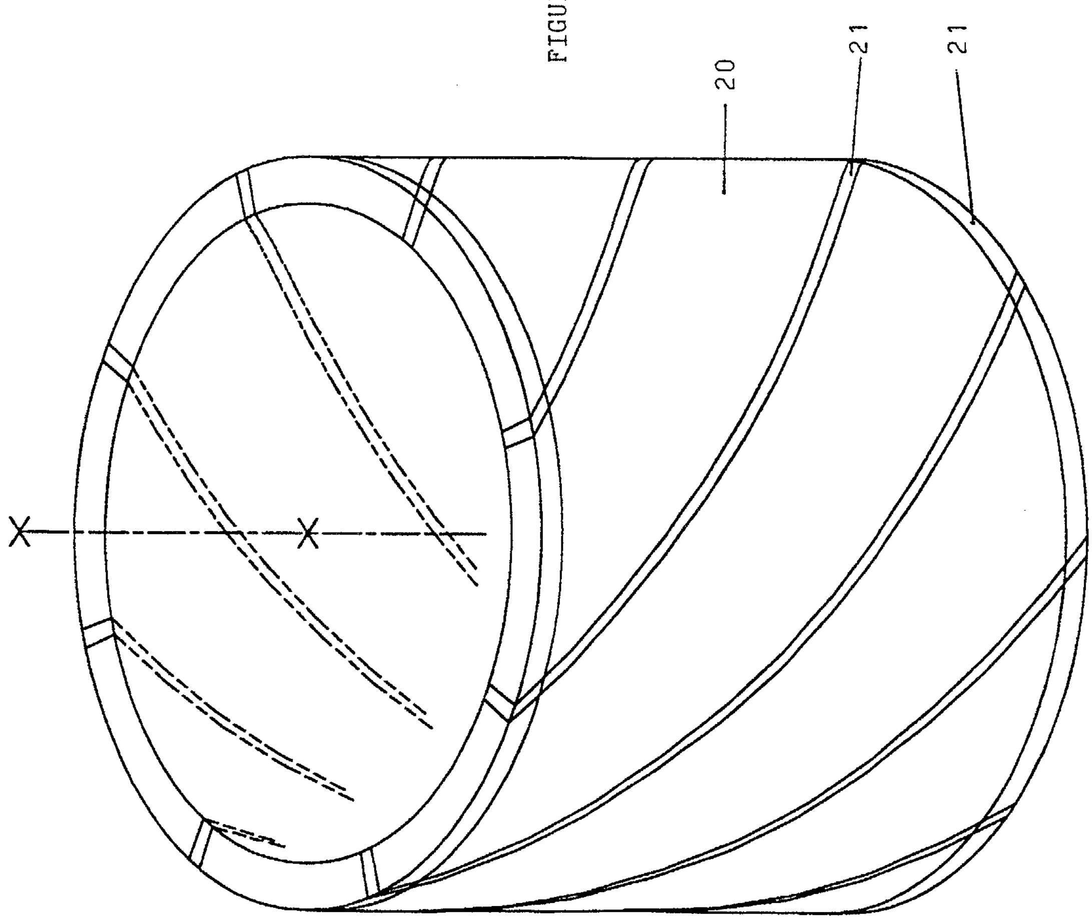


FIGURE 7a

FIGURE 8



SUBSTITUTE SHEET (rule 26)

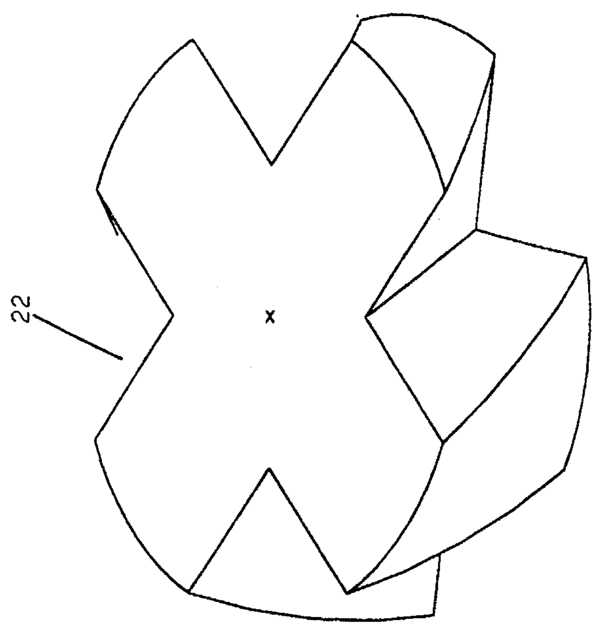


FIGURE 9b

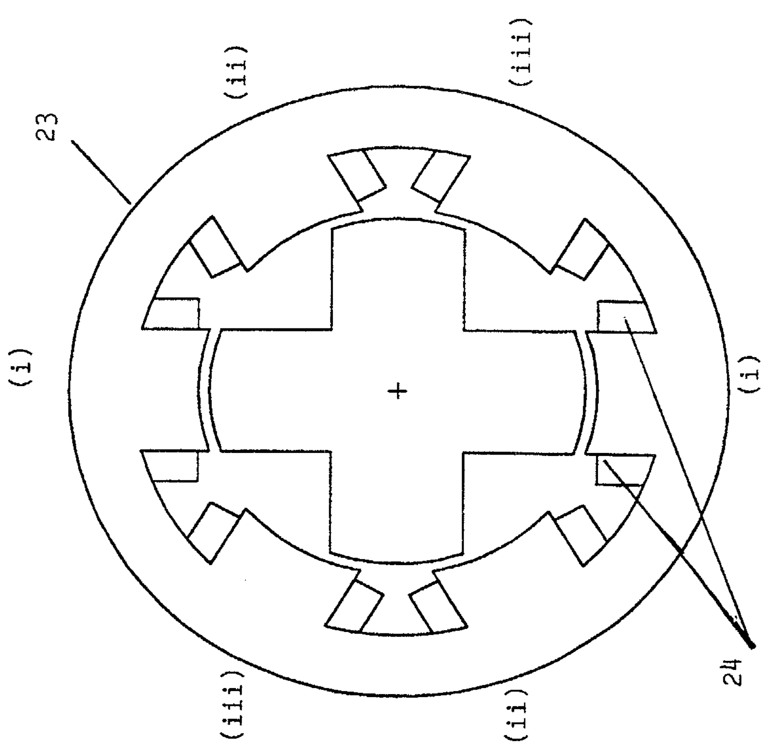


FIGURE 9a

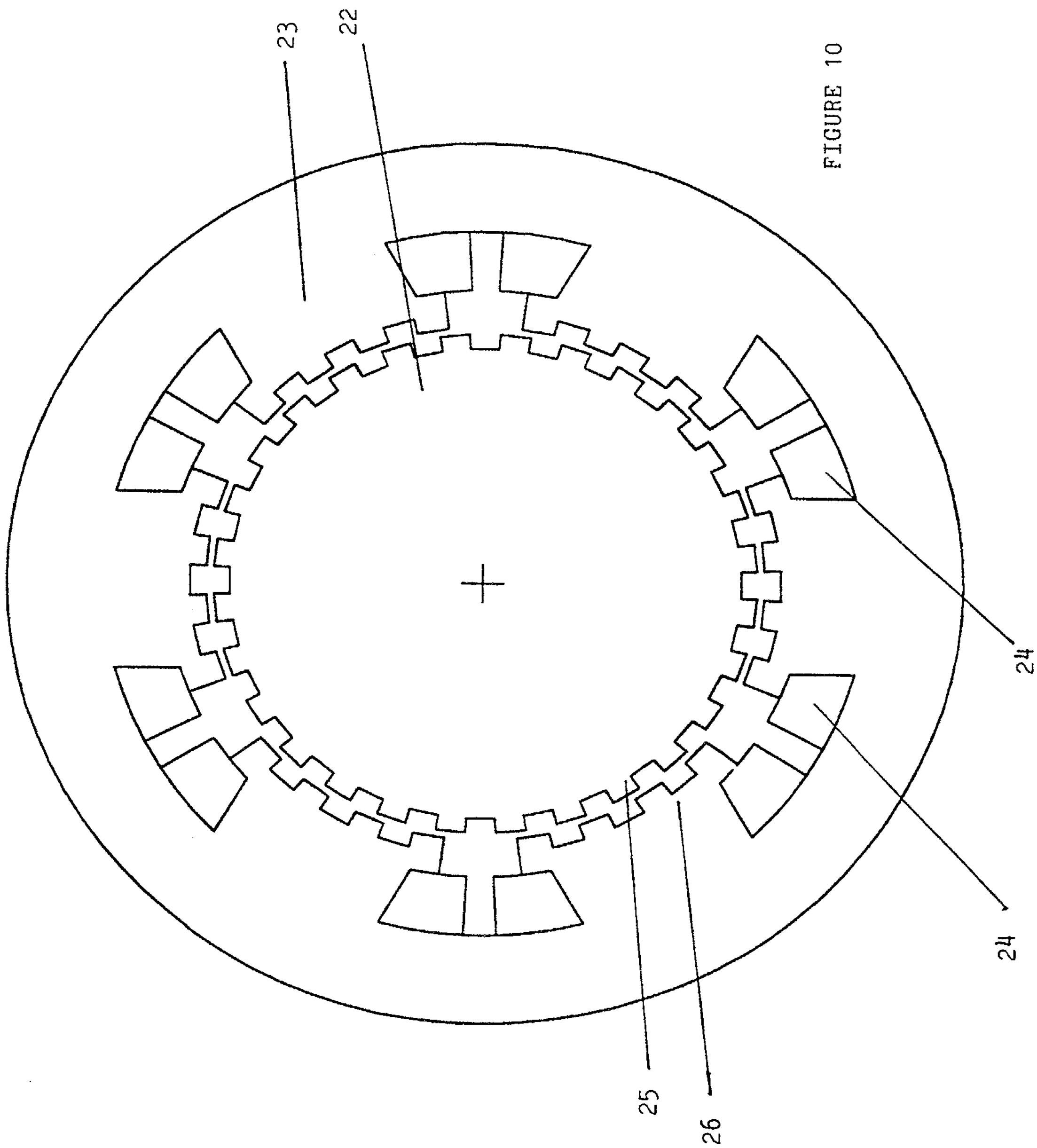


FIGURE 10

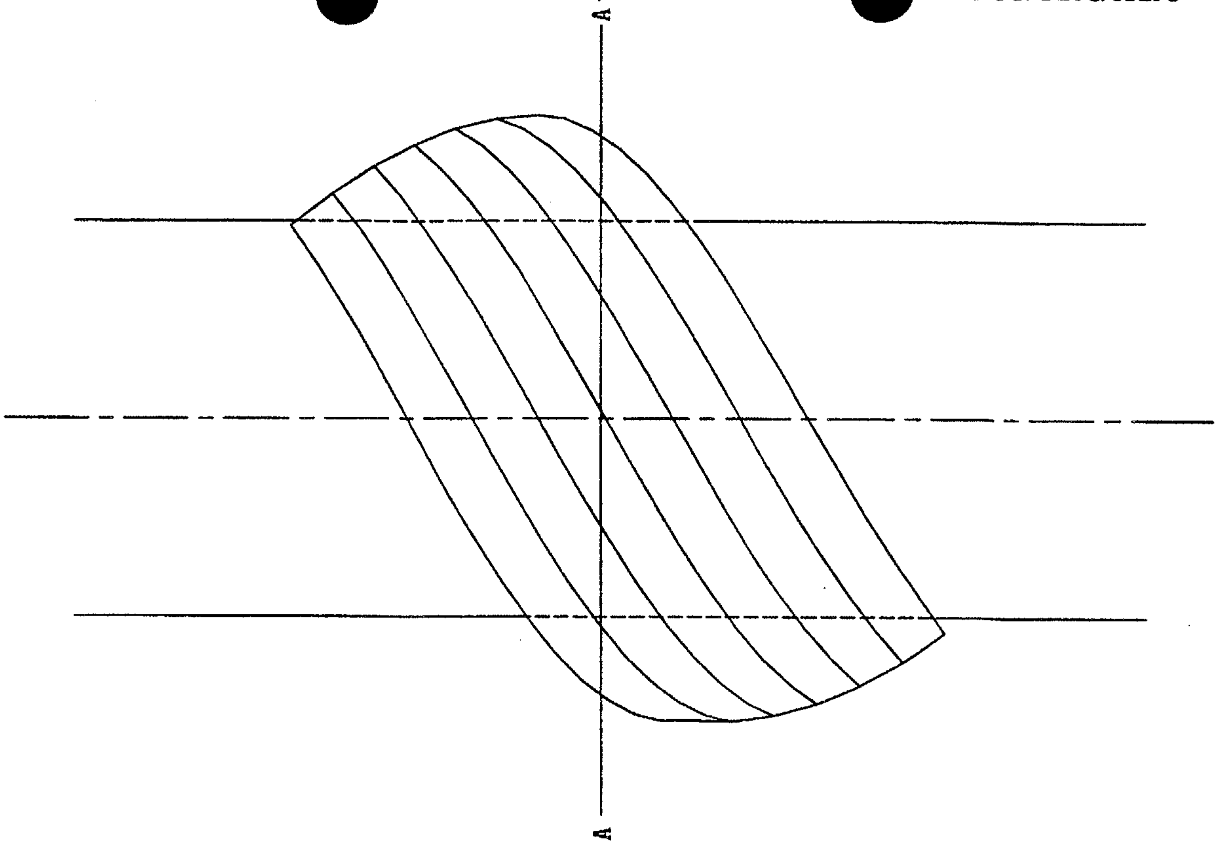


FIGURE 11b

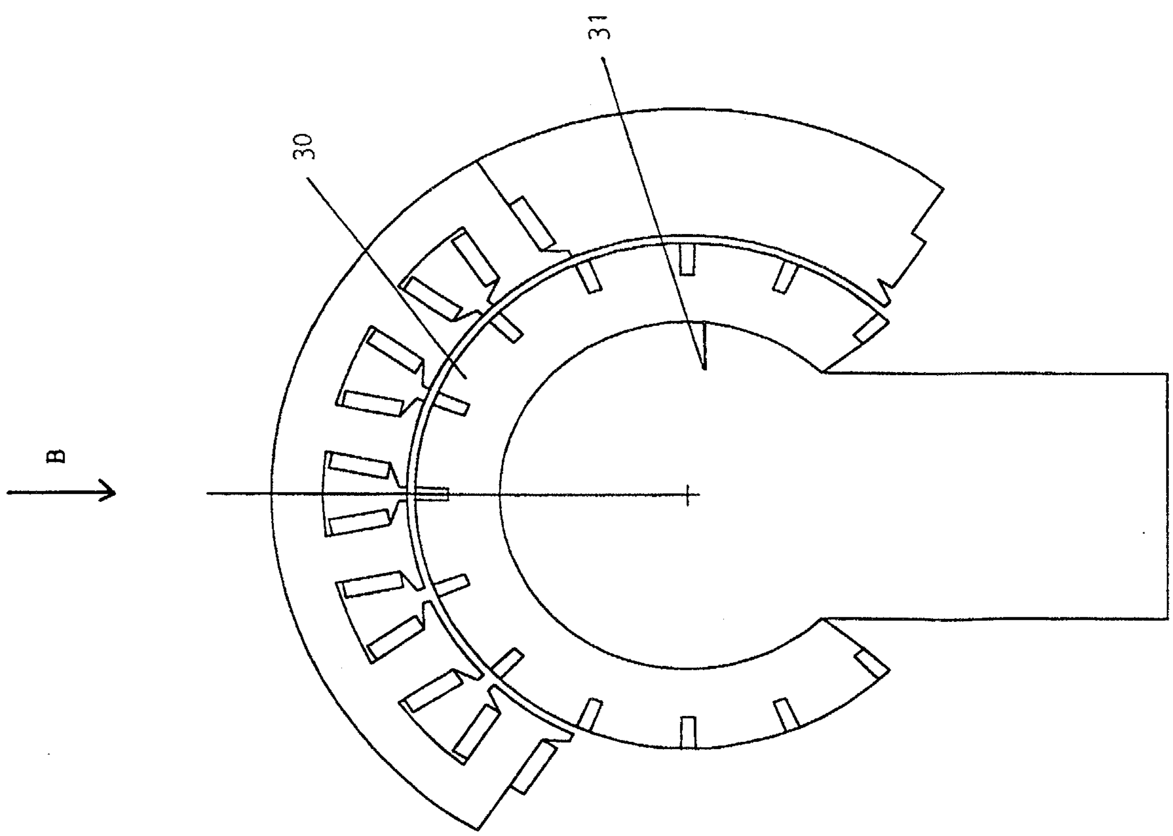


FIGURE 11a

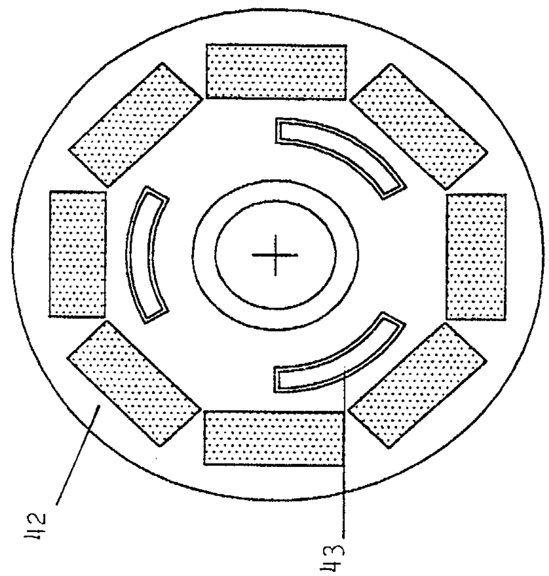


FIGURE 12b

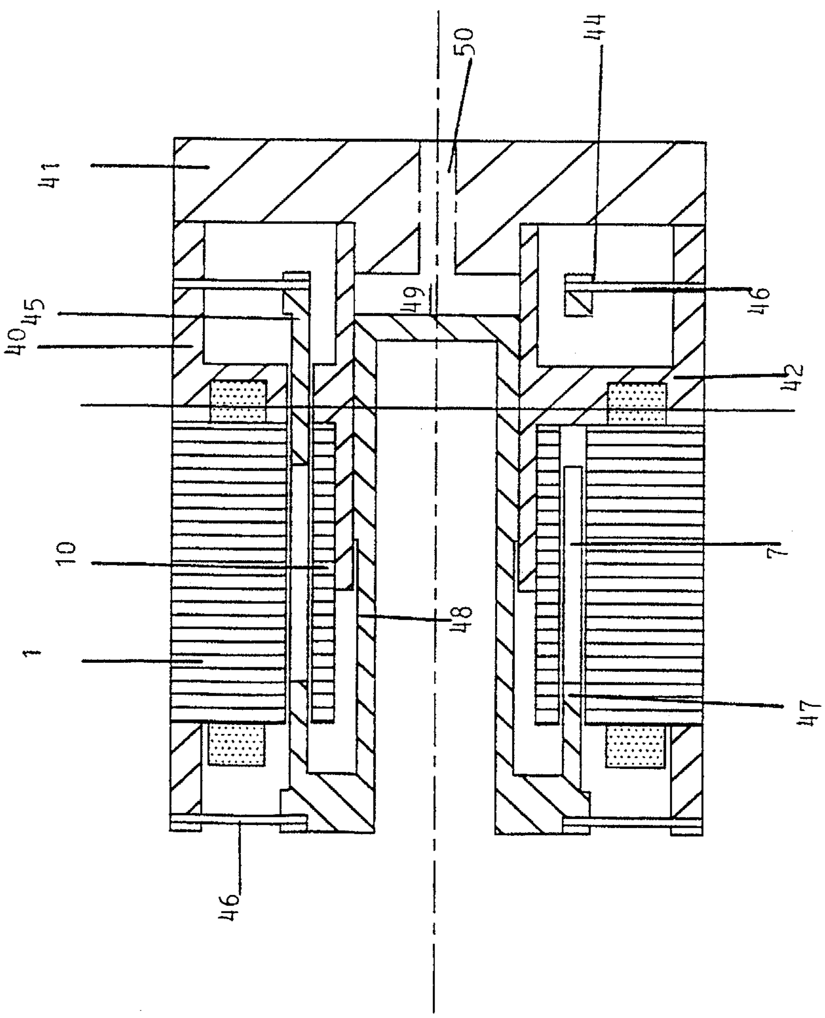


FIGURE 12a

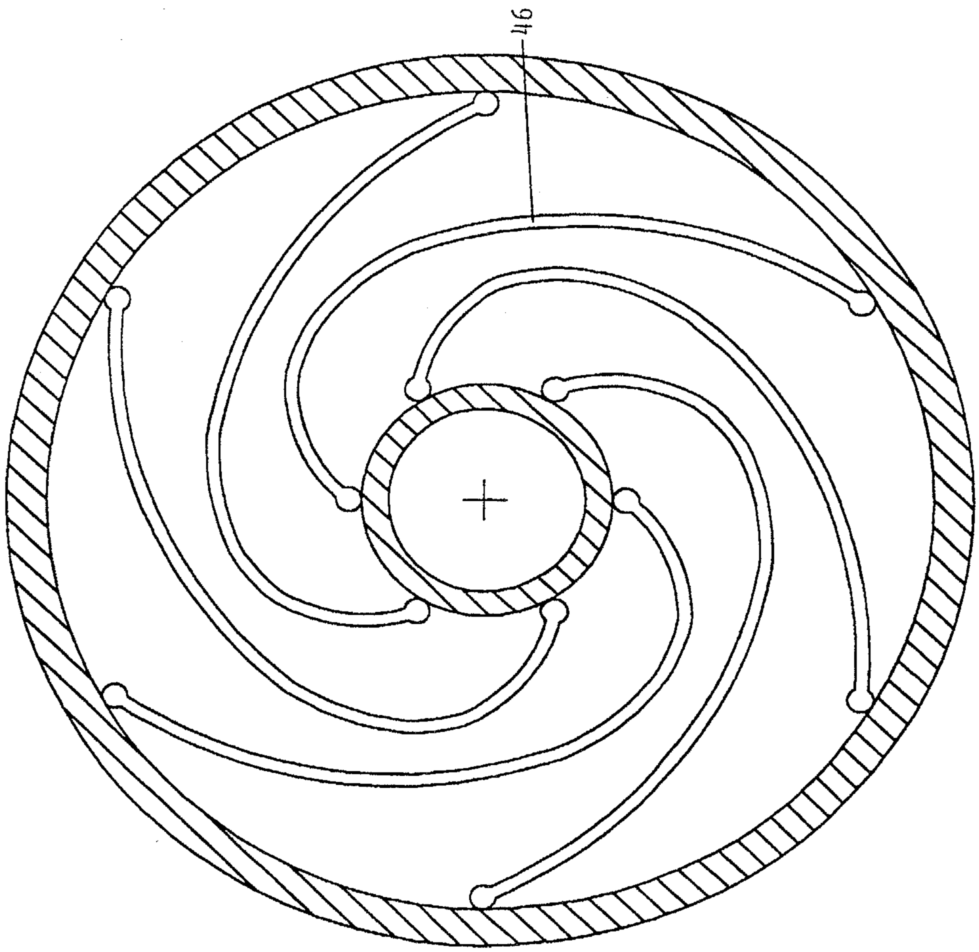


FIGURE 13

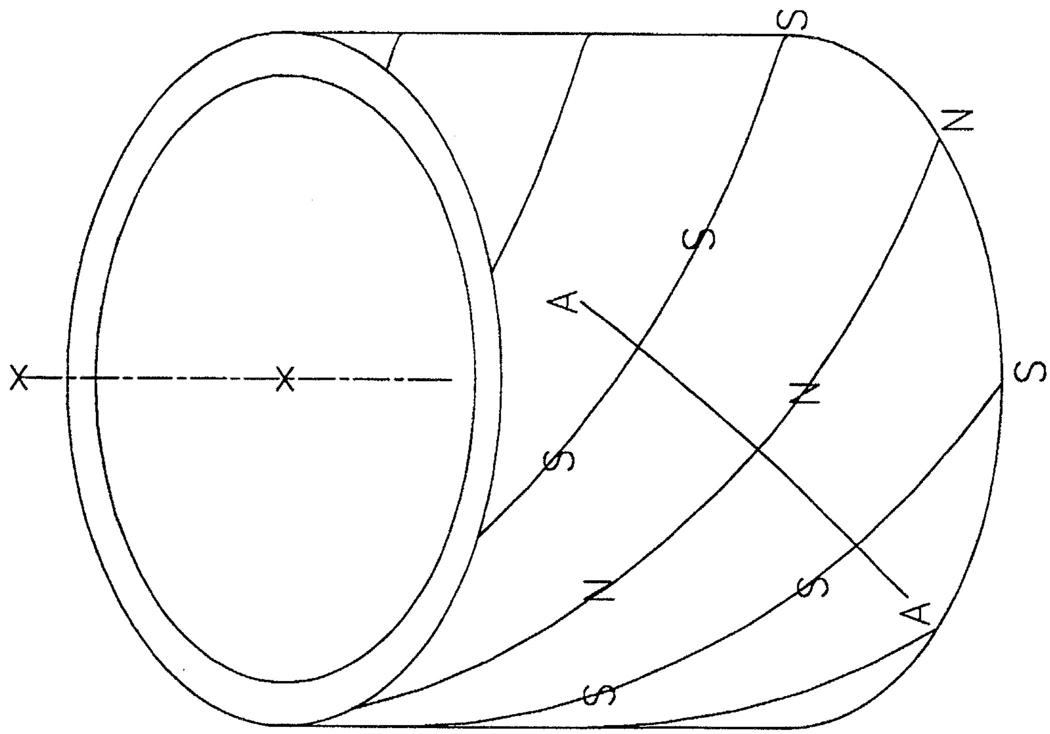


FIGURE 14a

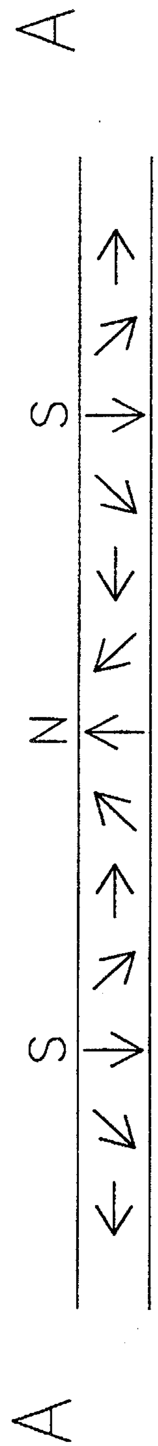


FIGURE 14b

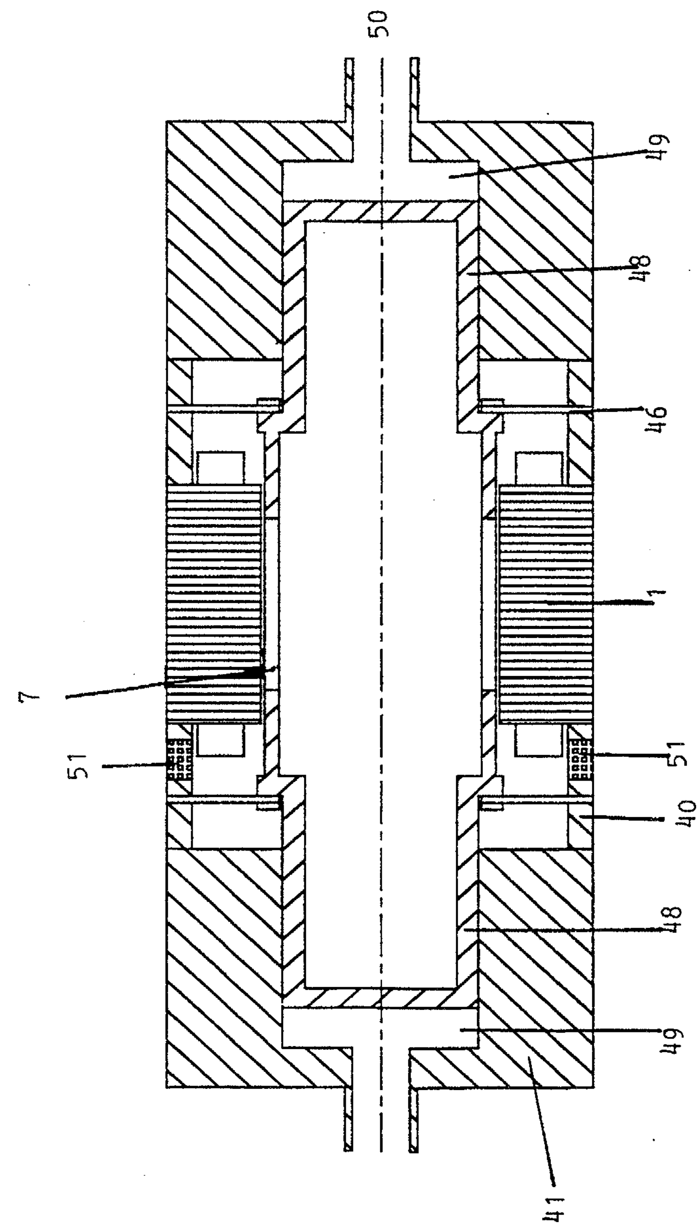


FIGURE 15